

# Glimpses of a strange star

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There are about 2000 gamma ray burst (GRB) events known to us with data pouring in at the rate of one per day. While the afterglows of GRBs in radio, optical and X-ray bands are successfully explained by the fireball model, a significant difficulty with the proposed mechanisms for GRBs is that a small amount ( $\leq 10^{-6} M_{\odot}$ ) of baryons in the ejecta can be involved. There are very few models that fulfill this criteria together with other observational features, among which are the differentially rotating collapsed object model [1, 2] and the "supernova" model [3]. These models generally invoke rapidly rotating neutron stars, and may be subject to uncertainties in the formation mechanisms and the equations of state of neutron stars. According to Spruit [2], the problem of making a GRB from an X-ray binary is reduced to finding a plausible way to make the star rotate differentially. We suggest that a model of strange star (SS) can naturally explain many of these bursts with not only their low baryon content [4], but the differential rotation which leads to an enhanced magnetic field that surfaces up and is responsible for GRBs.

The model of SS that we have suggested for some compact objects [5, 6, 7], has differential rotation as a consequence of its stratified structure as a natural phenomenon. It is based on a stable point in the binding energy as a function of density, for charge neutral, beta stable strange quark matter at about  $5 \rho_0$  where  $\rho_0$  is the normal nuclear matter density. It employs a quark-quark (qq) potential that has asymptotic freedom and confinement-deconfinement mechanism built into it. At high surface density of  $\sim 5 \rho_0$  at the radius  $R$  of the star, the qq - interaction is already small as compared to that in a hadron. Obviously the interaction is even smaller at the central density of  $\sim 15 \rho_0$ . Further we have a density dependent mass for the quarks which at such high central density ensures that the quarks have nearly current masses. The denser inner parts of the star are composed of quarks which are asymptotically free and nearly massless whereas the surface quarks are relatively more massive and interacting - leading to a peculiar structure which is different from that of a neutron star.

The energy density as a function of the radius  $r$  is shown in Fig. (1). To illustrate the peculiarity of the system we have also plotted the kinetic energy density (KE) of the quarks. The KE of the u and d quarks are each roughly half of the total which is less than the KE from the strange quark. The potential energy is negative and cannot be separated into parts. The interesting point to see is that the potential energy increases a little from the surface to the centre but not as much as one would expect, considering that the number density in the centre is about five times more than that near the surface. One should recall that the potential energy is a two-body term and thus is proportional to the square of the number.

Using this density variation of we put the surface  $r = R$  into rotation with a frequency  $\omega(R)$  about an axis. One can easily see that the central region on the equatorial plane

perpendicular to this axis rotates more than 100 times faster than the outer parts Fig. (2) to conserve angular momentum. The polar regions will rotate with  $\omega(R)$ . This natural differential rotation is the required one of the Kluźniak and Ruderman model [1].

According to this model, in a differentially rotating strange star, the internal poloidal magnetic field ( $B_0$ ) will be wound up into a toroidal configuration and amplified (to  $B_\phi$ ) as the interior part of the star rotates faster than the exterior. After  $N_\phi$  revolutions  $B_\phi = 2\pi B_0 N_\phi$ . The field thus amplified forms a toroid that encloses some strange quark matter. This magnetic toroid will float up from the deep interior only when a critical field value is reached that is sufficient to fully overcome the (approximately radial) stratification in the composition of the strange star.

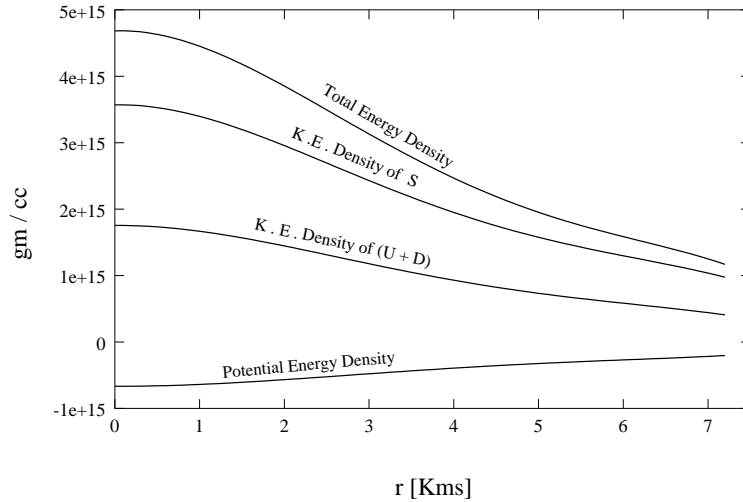


Figure 1: The total energy density, kinetic energy densities (KE) of the quarks and the potential energy density as functions of the radius inside a strange star of mass  $1.437 M_\odot$ . Recall that for relativistic systems the KE includes the mass so that the KE(S) dominates.

The model for strange quark matter that we have proposed is simple and is based on 't Hooft's pioneering work on large colour expansion [8]. His idea was to consider the number of colours,  $N_c$  in quantum chromodynamics to be a parameter of expansion for the field theoretic diagrams entering the expressions for variables like the energy of quark and gluon fields. Simple arguments then show that one can obtain a finite theory if one scales down the quark-gluon or gluon-gluon couplings by a factor of  $N_c^{1/2}$ . Then the quark loops are suppressed by a factor of  $\frac{1}{N_c}$  compared to planar gluon loops and non-planar gluon loops are suppressed by  $\frac{1}{N_c^2}$ . As explained by Witten [9], 't Hooft's expansion gives only tree level interactions between valence quarks for baryons in leading order in the  $\frac{1}{N_c}$  - expansion scheme.

The success of the large colour expansion model has also been stressed by [9] and others over the years. In particular, using a model potential designed to fit the heavier mesons [10], as well as lighter ones like the  $\rho, a, f$  - meson [11, 12] were able to fit baryons like the  $\Omega_-$  and others [13] using self consistent relativistic Hartree-Fock calculations. As already indicated the potential [10] has asymptotic freedom and confinement-deconfinement built into it. This is done very simply and ingeniously by modifying logarithmic momentum dependence of the running coupling constant in the potential :

$$V(q^2) = \frac{12\pi}{27} \frac{1}{\ln(q^2/\Lambda^2)} \frac{1}{q^2} , \quad (1)$$

to by replacing  $\frac{1}{q^2} \ln(q^2/\Lambda^2)$  by  $\frac{1}{q^2} \ln(1 + q^2/\Lambda^2)$ . For large  $q^2$  the original coupling eq.(1) is recovered whereas for large distance interaction when the momentum transfer  $q^2$  is small one gets a  $\frac{1}{q^4}$  dependence equivalent to a string-like tension  $\Lambda^2 |\vec{r}_1 - \vec{r}_2|$  in the particle coordinates. For dense systems the  $q^2$  is replaced by  $q^2 + D^{-2}$  where  $D^{-1}$  is the well known Debye screening factor.

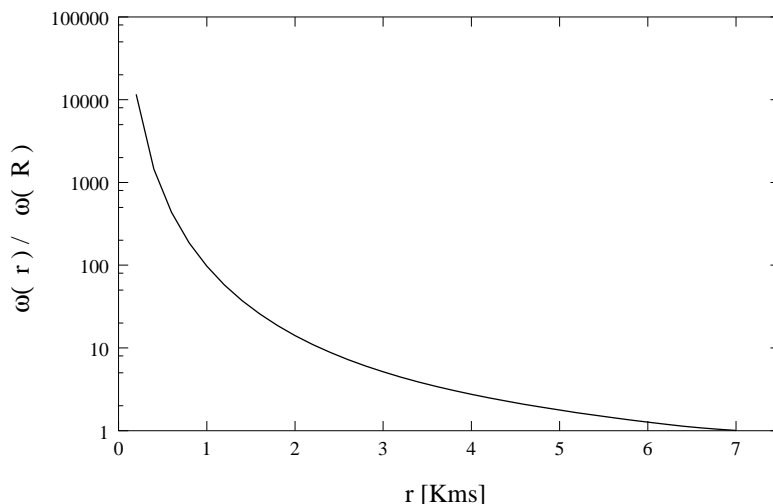


Figure 2: The circular frequency in the equatorial plane at various radii inside a strange quark star

One further ingredient is very important and this has to do with the fact that QCD possesses approximate chiral symmetry in the sense that the current quark masses of u, d, s are small but in the ground state this symmetry is broken leading to massive so-called constituent quarks. At high density chiral symmetry is believed to be restored and this has been parameterized by us with a single parameter  $\nu$  in a form :

$$M_i = m_i + 310 \operatorname{sech}\left(\nu \frac{\rho}{\rho_0}\right). \quad (2)$$

where  $m_i = 4, 7$  and  $150$  for  $i = u, d$  and  $s$  respectively (all in MeV). The suggestion that compact objects like SAX J1808.8-3658, Her X-1, 4U 1820-30 or 4U 1728-34 [5, 6, 7] are strange stars give us the possibility to fix the chiral symmetry restoration parameter  $\nu$  (eq. 2) from astronomical data. This amounts to constraining microscopic physics of light objects in terms of some of the densest objects known in the universe. Although our model is simple the basis is robust and we believe that the results will retain their validity even if more refined calculations are done in the future.

We would like to point out that the strange star candidate SAX J1808.8-3658 is the fastest rotating X-ray pulsar with surface rotation frequency  $\omega(R) \simeq 400$  Hz, shown in the power spectrum as a very sharp line at that frequency in Wijnands and van der Klis [14]. It was suggested that it may appear as an eclipsing radio pulsar during periods of X-ray quiescence by Chakraborty and Morgan [15]. Recently this has been confirmed when radio signals were found to be present, a day after the X-ray flux suddenly deviated from exponential decay and began to decrease rapidly [16], suggesting that LMXB-s are progenitors of millisecond radio pulsars (MSR). This completes the following scenario : the birth of a strange star may be due to accretion from its binary partner - leading sometimes to such high rotational frequency that the star explodes to a GRB. Those that survive due to slower rotation become LMXB-s like the SAX J1808.8-3658. it may continue to prey on its partner and become closely related ‘black widow’ MSR which are evaporating their companions through irradiation as suggested in [15]. From the stability of SAX J1808.8-3658 we can safely assert that only those strange stars rotating faster than a critical  $\omega(R)_{crit} > 400$  Hz may acquire the critical magnetic field and fly off to a GRB mode.

There are several possible channels for strange star formation: type II/Ib supernovae, accretion-induced collapse of white dwarfs, and conversion from accreting neutron stars in binary systems [17]. The new born strange stars could rotate at periods  $\leq 1$  ms because of rapid rotation of the progenitor stars due to either contraction or mass accretion. Furthermore, they are not subject to the  $r$ -mode instability [18] which slows rapidly rotating, hot neutron stars to relatively long rotation periods via gravitational wave radiation. Thus differential rotation may naturally occur in the interiors of these strange stars as discussed above.

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